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CO_2 Laser Physics and Tissue Interactions in Skin

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Background and Objectives: **The theoretical model of CO_2 laser tissue interaction appeared to be too simplistic. To explain the reactions seen in skin, a more complex model was needed. We hoped to correlate the clinical-histologic patterns of CO_2 laser tissue interactions.**
Study Design/Materials and Methods: **The Ultrapulse CO_2 laser was used on normal and pathologic skin conditions. Clinical observations were correlated with histologic examinations of biopsies.**
Results: **It was possible to demonstrate cavitation at the dermal-epidermal junction 2–3 diameters beyond the actual spot of CO_2 laser contact with the skin. Dermal heat damage was seen as homogenization of collagen 1–2 diameters beyond the spot of laser contact. This flow of energy laterally at the dermal-epidermal junction and vertically down the skin follicles was both clinically beneficial and detrimental. Beneficially, superficial skin lesions separated at this junction and were easily removed. The heat coagulation of the dermis facilitated lesion removal without bleeding. The clinician had a better view of the pathology and could find focal zones of deeper pathology that could be easily re-treated. Detrimentally, this extended damage delayed wound healing and led to persistent erythema.**
Conclusion: **These clinical-histologic correlations have provided a better understanding of CO_2 laser tissue interactions in skin. It has been possible to take advantage of these findings to remove pathologic skin conditions more efficiently. Lasers Surg. Med. 24:113–121, 1999. © 1999 Wiley-Liss, Inc.**

Key words: **delayed wound healing; skin rejuvenation; therapeutic index; cavitation energy**

INTRODUCTION

Although the short pulse CO_2 lasers are becoming the gold standard in skin resurfacing [1–4], adverse sequelae such as scarring or persistent erythema remain as possibilities [5]. Investigators have discussed laser energy in relationship to selective epidermal damage [6], lateral thermal damage [7], and scar formation [8] but a model to better understand these laser effects on skin has been unavailable.

It became obvious during our clinical trials that models of CO_2 laser physics and tissue interactions described by the theoretical physicists [9–10] did not completely apply to tissue of such varying densities as skin. Clinically, it appeared as the Ultrapulse CO_2 laser sent a shock of energy along tissue planes. The epidermis bubbled off the underlying dermis. The classic cone-shaped model of vaporization, necrosis, and thermal damage was too simplistic to explain reactions in tissue as complex as skin. In order to document these clinical-histological correlations, multiple biopsies were taken at different fluences during the re-

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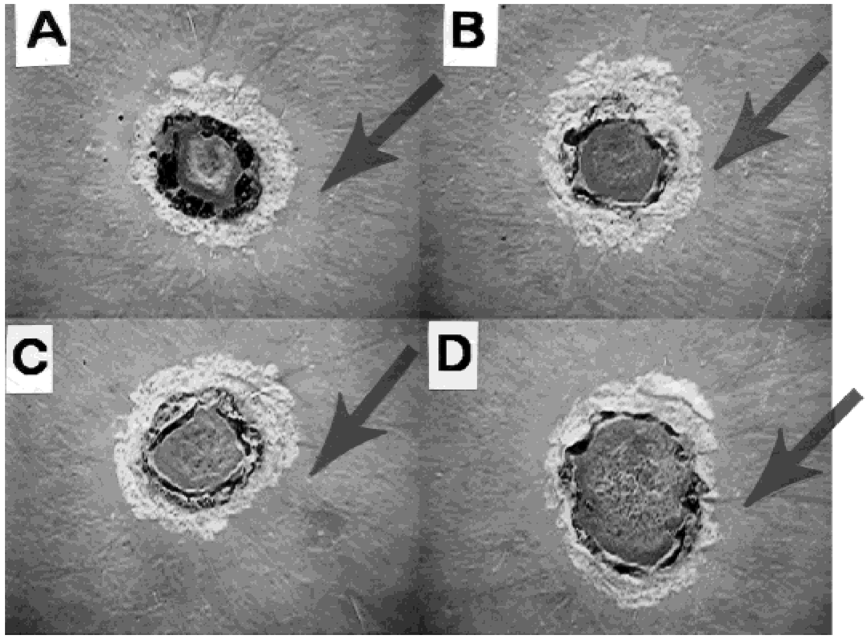


Fig. 1. An actual photograph (×90) of the direct laser contact points on normal skin. Note the zones of cavitation(↓) of 125 **(A)** and 450 **(D)** mJ and the wider zones of vaporization produced by the higher fluences. The dermis is often exposed after one pass at 450 mJ; 250 to 350 mJ **(B,C)** provide the best therapeutic index—the most vaporization with the least cavitation and heat damage (Cosmax 200 video camera, Medicom Systems, Wheeling, IL).

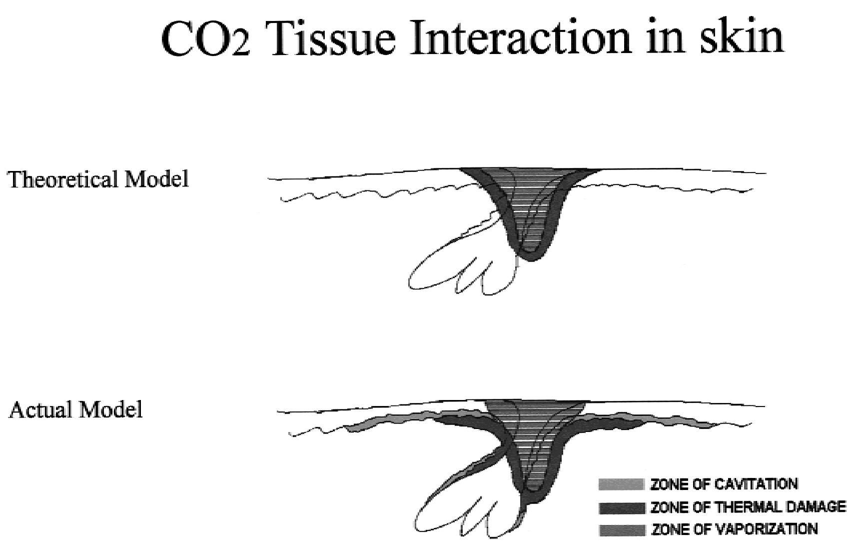


Fig. 2. The theoretical model did not correlate with the findings seen in skin. The cavitation effects spread out 2–3 diameters beyond the actual physical point of contact of the laser beam. The zones of homogenization of collagen spread out 1–2 diameters beyond the zone of physical contact. Not only was there lateral spread of effects but there was a vertical spread down into the skin appendages such as the hair follicle. These multiple planes of tissue densities behaved differently than the theoretical model.

moval of sun damaged skin and the removal of various skin lesions. This opportunity helped us create a new model of Ultrapulse CO_2 laser physics and tissue interactions in skin. This report summarizes these findings.

MATERIALS AND METHODS

The Ultrapulse CO_2 laser (Coherent, Inc., Palo Alto, CA) was used for these clinical-histologic correlations. Isolated skin lesions were

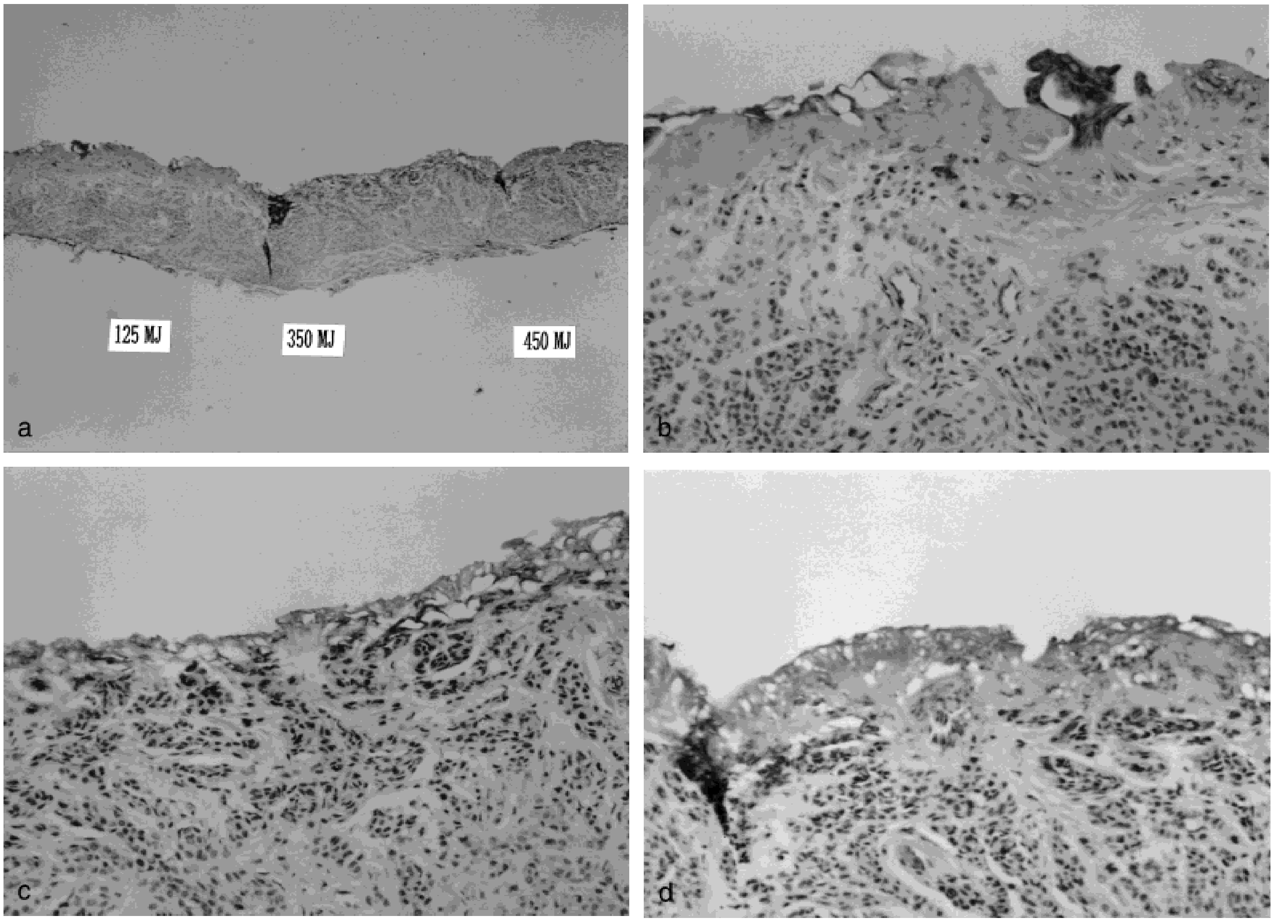


Fig. 3. **(a)** The different fluences between 100 and 500 mJ produced different clinical effects. At the lower millijoule settings there was extensive homogenization of collagen, reflecting heat damage. At the optimal laser setting of 350 mJ there was clean vaporization of epidermis without extensive heat damage. 450 to 500 mJ produced vaporization that was so intense that vacuoles and basophilic degeneration was present in the collagen. **(b)** A close-up of the effects of 125 mJ demonstrating the extensive homogenization of collagen. Much of the laser energy is absorbed as heat by the dermis, not by vaporization of the epidermis. **c:** At the setting of 350 mJ, there is a clean vaporization of the epidermis without extensive heat damage. **d:** At 450 to 500 mJ, the vaporization is so intense that it produces vacuoles and basophilic degeneration of the upper dermis.

treated with the Variable Handpiece or the Collimated Handpiece (Tru-spot®) at millijoules ranging in energy settings of 100 to 500 mJ. Skin resurfacing was accomplished with the Computer Pattern Generator® (CPG) Handpiece at standard settings (Fig. 13). Following vaporization, lesions were removed with a disposable curette (Acuderm, Inc., Ft. Lauderdale, FL) or a wet gauze.

Biopsies were taken following laser vaporization of skin for the clinical-histologic correlations. Tissue was fixed in Formalin, mounted in paraffin, sectioned at 6 μm, and stained with hematoxylin-eosin stain. The two authors examined the resulting preparations microscopically.

RESULTS

It became apparent during these clinical-histologic correlations of skin that the physicist's model of cone-shaped CO_2 laser effects demonstrating a zone of vaporization, a zone of necrosis, and a zone of thermal damage was too simplistic to explain these reactions. Clinically, there was extensive lateral damage beyond the spot size of the laser beam. One observed at lower laser fluences a bubble (cavitation) spreading out beyond the target (Fig. 1). The complete normal or pathologic epidermis slipped off easily with a wet gauze or curette. As the fluence increased, the zone of vaporization became more dominant and the lateral spread of cavitation energy was less pronounced. The model of Ultrapulse CO_2 laser-skin interaction was redrawn to demonstrate this lateralization of laser effects between the tissue planes of skin (Fig. 2).

At the lower fluences of 100 to 250 mJ, the tissue specimens demonstrated large zones of col-

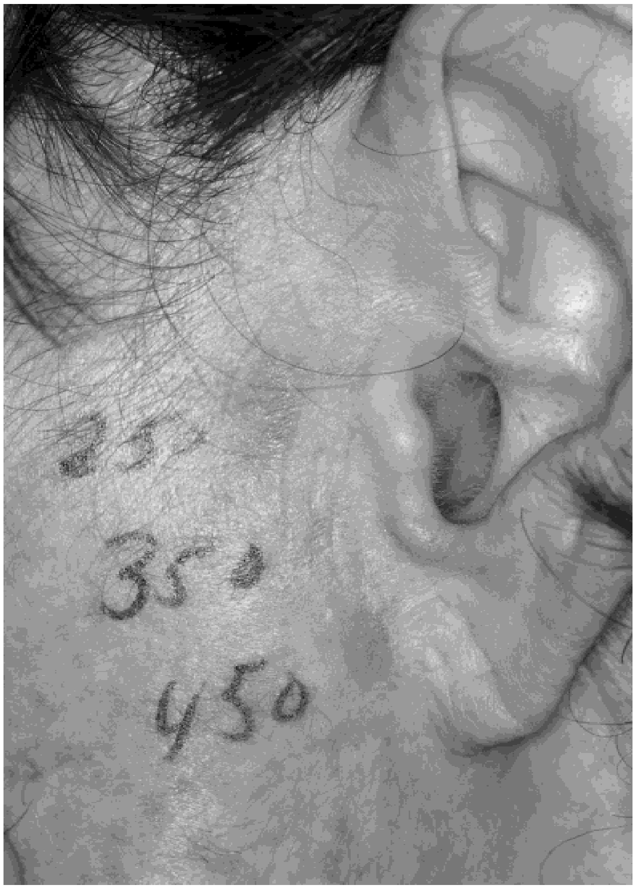


Fig. 4. The clinical effects at different fluences after 3 weeks. At lower millijoules of energy there is delayed wound healing because of the extensive heat damage. At 350 mJ, there is a clean vaporization of tissue and rapid healing. At 450–500 mJ there is more damage from the intense vaporization and persistent erythema developed during the healing phase.

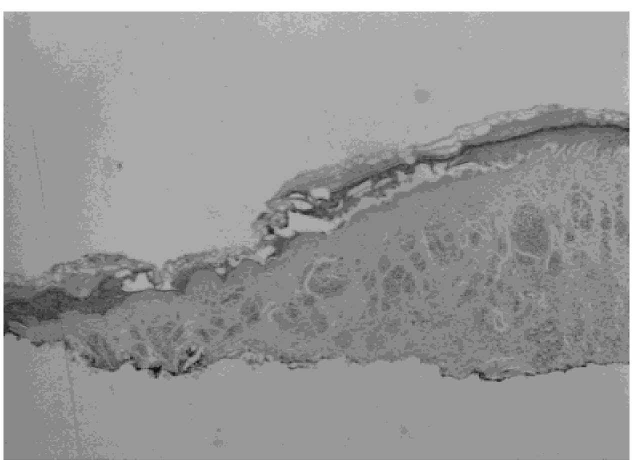


Fig. 5. This specimen demonstrates lateral damage from the cavitation effect at least two diameters beyond the physical contact point of the laser beam. The homogenization of collagen is also apparent at least one diameter beyond the actual laser contact point.

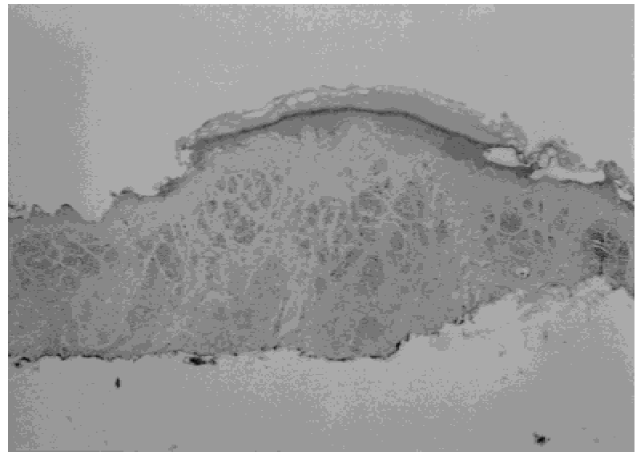


Fig. 6. It is not necessary for the actual physical contact of the laser beam to overlap as the spread of the cavitation energy joins contact points and produces a smooth zone of deepithelization. Wet gauze wiped over this area demonstrates a shiny, uniform, denuded skin.

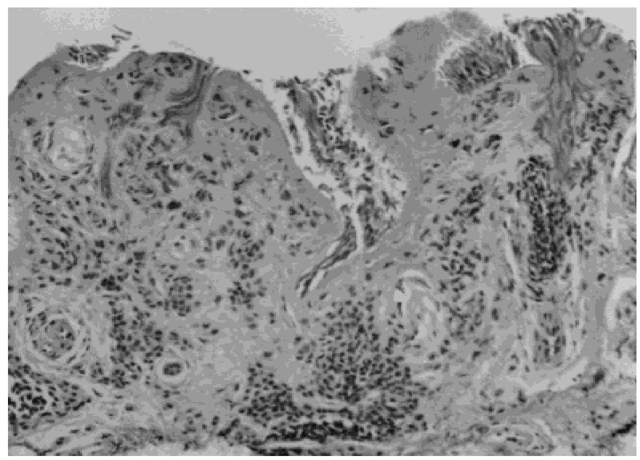


Fig. 7. Not only does the cavitation energy spread horizontally but it spreads vertically into the hair follicles approximately 300 to 400 μm below the actual contact point of the laser beam. The homogenization of collagen also extends down the follicle wall for 100 to 200 μm.

lagen homogenization reflecting heat damage. The best therapeutic index was at 350 mJ. At this energy setting there was the most vaporization for the least heat damage. At 450 to 500 mJ, the vaporization zone was more dramatic, producing vacuoles in the dermis with an accompanied basophilic zone of collagen damage. Laser interactions at 350 mJ were least damaging (Fig. 3). This was also seen clinically as lower fluences and higher fluences than 350 mJ produced delayed healing and persistent erythema (Fig. 4).

The lateral extent of the damage was remarkable. The zone of cavitation at the dermal-

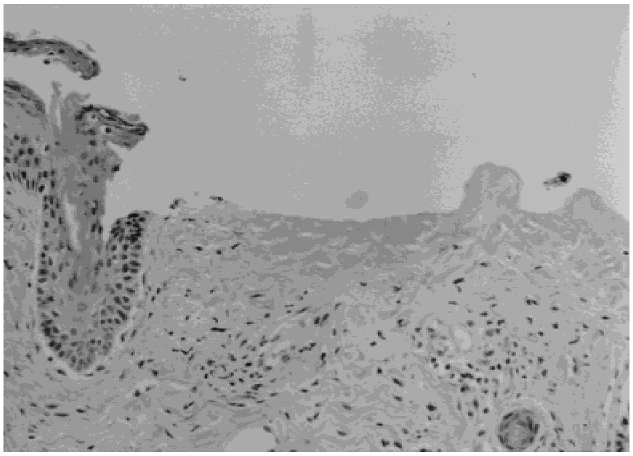


Fig. 8. The extreme accuracy of the laser beam is demonstrated here. On the initial pass at 300 to 350 mJ the zone of vaporization of normal skin is 75 to 100 μm. It is impossible to reproduce this accuracy with a chemical peel or with the diamond fraise abrasion.

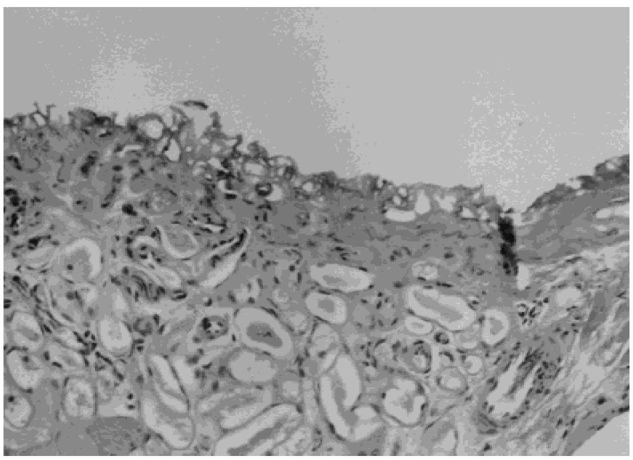


Fig. 9. This hemangioma demonstrates the homogenization of serum and red blood cells within the upper dermal capillary plexus following treatment with the Ultrapulse CO_2 laser. This zone of thrombosis is helpful in providing a zone of hemostasis during tissue removal so areas of pathology can be seen clearly.

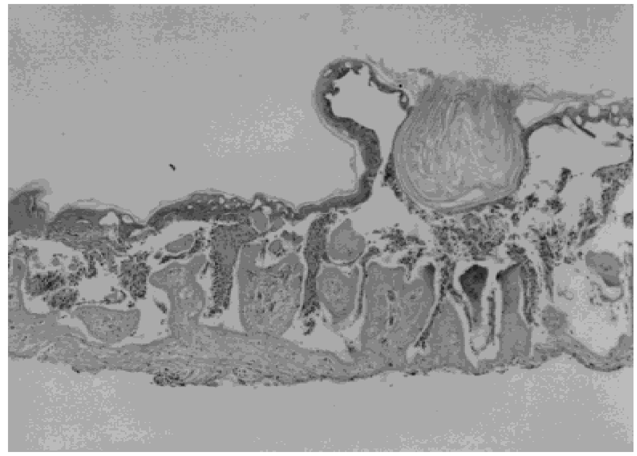


Fig. 10. The pretreatment of a keratoses with the Ultrapulse CO_2 laser produces a dramatic cleft at the dermal-epidermal junction. This permits clean removal of the lesion without bleeding. Any deeper foci of pathology can be easily examined and re-lasered and re-curetted, clearing the lesion at a very superficial level.

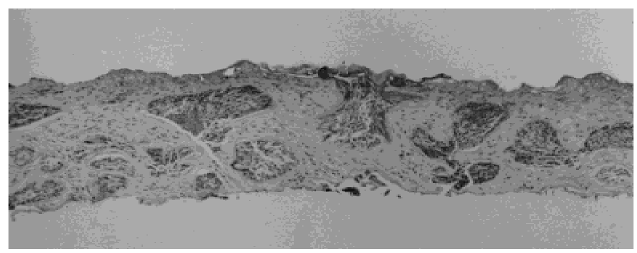


Fig. 11. The natural cleft between the dermis and a basal cell cancer is augmented by pretreatment with the Ultrapulse CO_2 laser. This allows better removal of the skin cancer and, as there is diminished bleeding, an identification of any deeper foci that can be re-lasered and re-curetted.

epidermal junction spread out 2–3 diameters beyond the contact point. The zone of homogenization of collagen was approximately double the diameter of laser contact. There was actually more collagen damage lateral to the direct contact zone than immediately below the point of contact (Fig. 5). It was obvious both clinically and histologically that the laser beam did not need to overlap (Fig. 6) as there was adequate lateralization of energy to blend effects between two adjacent nonoverlapping hits. The wet debriding sponge removed a complete sheet of epidermis between adjacent laser contact points leaving a uniformly denuded papillary dermis.

This zone of cavitation at the dermal-epidermal junction did not spare the skin appendages. The energy spreading down the hair follicle produced cavitation and a zone of collagen damage 300 to 400 μm down the follicle wall (Fig. 7), well beyond the zone of vaporization.

By observing these normal skin and pathologic conditions it was possible to extrapolate findings not apparent on an experimental agar plate or an experimental optical bench. For example, the extreme accuracy of the laser over a chemical peel or dermabrasion was apparent (Fig. 8). Seventy-five to one hundred micrometers of tissue was vaporized every time. This provided a pleasing skin rejuvenation but also provided an accuracy for the removal of pathologic skin condi-

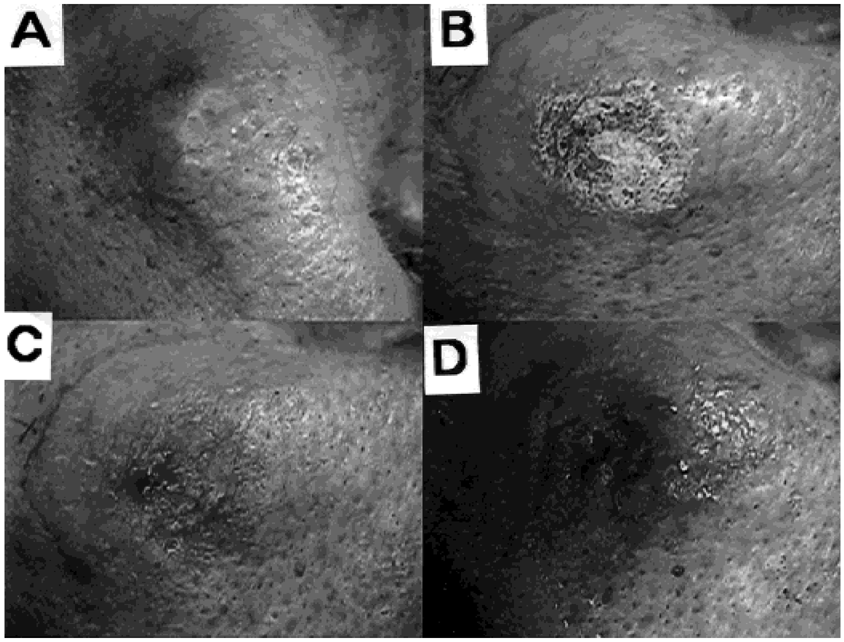


Fig. 12. An actual photograph (×30) of a basal cell carcinoma **(A)**. The lesion after desiccation with the Ultrapulse CO_2 laser **(B)**. After curettment the foci of cancer are still present **(C)**. After re-lasing and re-curetting all the deep foci of cancer have been removed **(D)** (Cosman 200 video camera, Medicom Systems, Wheeling, IL).

tions unequaled by liquid nitrogen, chemical peeling, dermabrasion, or the scalpel.

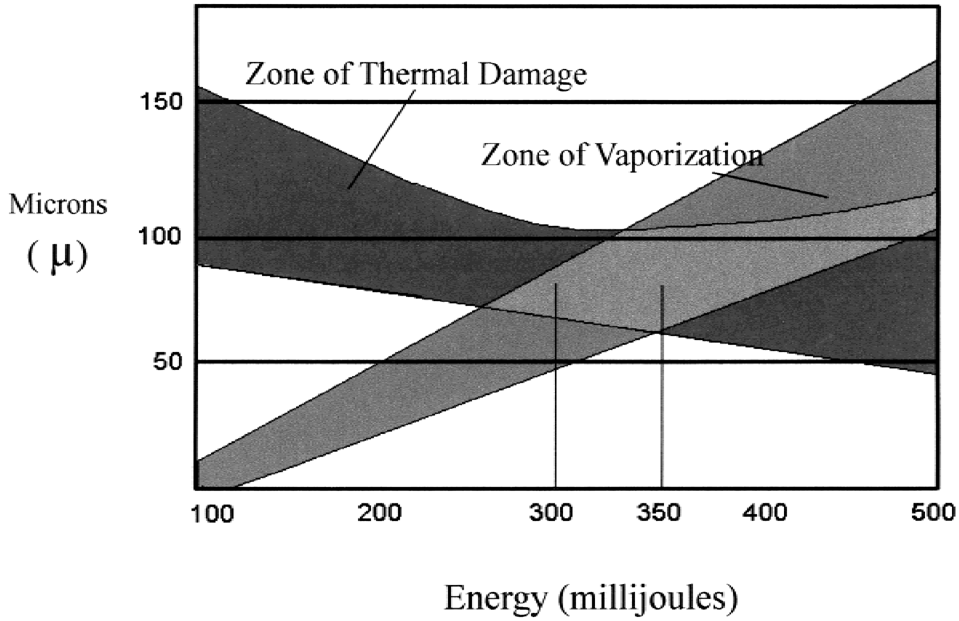
This zone of heat damage also produced blood vessel thrombosis of the dermal capillary plexus. This was quite helpful for removing a vascular lesion as the usual blood flow blinding the clinician was not a problem. This allowed a more accurate appraisal of skin lesions. Deeper extensions of actinic keratoses, verruca vulgaris, and skin cancers could be easily seen and then removed (Fig. 9). This zone of cavitation producing dermal-epidermal separation was most helpful in the removal of keratosis such as seborrheic or actinic keratoses. These lesions actually lift off with the laser and fall off with the abrasion of the curette (Fig. 10). Thus, the clinician is always in the correct plane, not taking off too much normal skin or leaving any pathology. With the use of occlusive dressings these lesions healed rapidly without marked hypo- or hyper-pigmentation or persistent erythema.

This laser assistance was also helpful in removal of basal cell skin cancers, especially in complicated areas around the nose (Fig. 11). The cavitation from the vapor of the CO_2 laser augmented the natural cleft that develops between a basal cell cancer and normal skin. Thus, the cancers could be easily shelled out with the curette. This removed the bulk of the lesion and, since there was reduced bleeding, any deep focal points could be visualized. These lesions could be re-lasered and scraped again until a clean base of normal dermis was visualized (Fig. 12).

DISCUSSION

It became apparent during clinical-histologic correlations that the simple cone-shaped model of laser effects on an artificial media or on an optical bench was not adequate to explain the complexities of CO_2 laser interactions with skin. The three zones of laser effects were complex in the actual human model. The zone of cavitation from the steam cloud extended laterally and vertically at the dermal-epidermal junction. This cavitation spread down the walls of skin follicles approximately 300 to 400 μm (Fig. 2).

The characteristics of the laser-tissue interactions also changed with the fluence of the CO_2 laser. For example, at lower fluence (100 to 250 mJ) the zone of homogenization of collagen (reflecting the heat damage) was the significant part of the laser injury. Around 350 mJ, the dynamics changed. There was excellent vaporization of the tissue without much accompanying heat damage. This pattern changed at 450–500 mJ where the power of vaporization was so significant that it created vacuoles in the dermis and the reappear-



The Zone of Thermal Damage diminishes as the Zone of Vaporization increases up to 350 millijoules of energy. Thereafter, both Zones increase together producing vacuoles and basophilic degeneration of collagen. 300-350 millijoules of energy yields the best therapeutic index of efficacy versus safety.

Fig. 13. Ideal settings for skin resurfacing using the ultrapulse CO_2 laser.

ance of collagen homogenization (Fig. 3). This was seen clinically as more rapid healing at a fluence of 350 mJ compared to 250 or less mJ. At the lower fluence heat damage delayed the wound healing. At 450 to 500 mJ the extensive vaporization and vacuolization of collagen produced another significant wound. These lesions developed persistent erythema (Fig. 4).

The zone of cavitation was present 2–3 diameters beyond the actual contact point of the Ultrapulse CO_2 laser. The zone of heat damage spread out 1–2 diameters beyond the contact point (Fig. 5). This allowed us to define a zone of damage from the CO_2 laser as approximately three times the diameter of the actual contact point of the laser. Thus, the physical damage produced by the laser beams extends way beyond the spot of tissue debris seen on the surface of the skin. It is not necessary or advantageous for the laser beams to overlap as the cavitation damage produces a wide zone of communication between laser spots. The clinician can remove a homogeneous layer of denuded skin with a wet gauze when these beams do not overlap (Fig. 6). It is obvious that the Ultrapulse CO_2 laser effects compound when the beams do overlap.

The delay in wound healing following a laser burn is easily appreciated when one examines the lateral and vertical extent of this heat damage. The energy flows down the follicle 300 to 400 μm (Fig. 7). This disorganizes the zone of proliferation of new skin cells and forces regeneration to occur several hundred microns deeper than the usual proliferation zone following a dermabrasion or a moderate chemical peel. This extent of deep damage of approximately 300 to 400 μm makes this wound somewhat equivalent to the Baker-Gordan peel where zones of deep damage of 500 to 1,000 μm have been documented [11]. This may explain the persistent erythema that is common to both laser and phenol resurfacing. However, the extreme accuracy of the laser wound may ex-

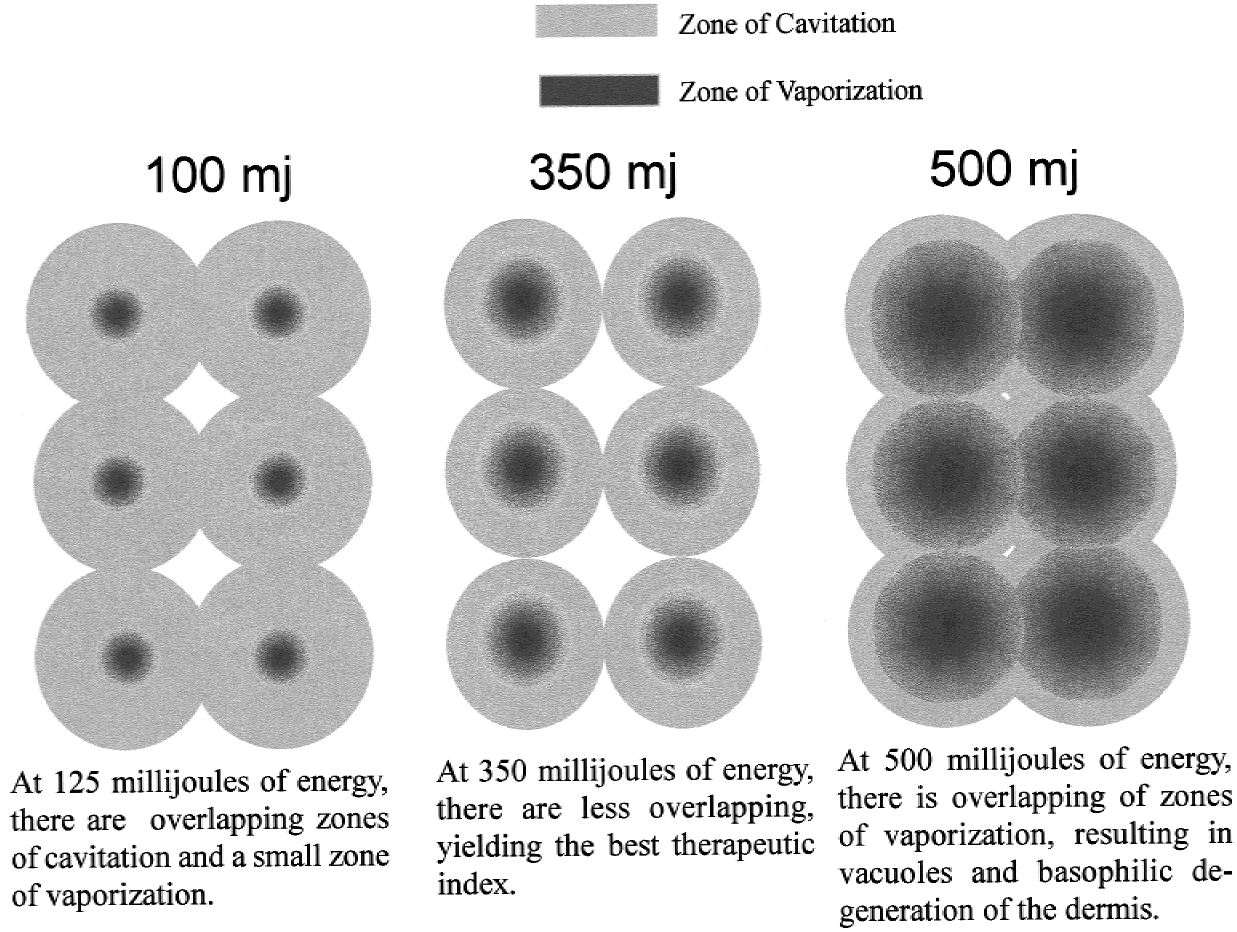


Fig. 14. The zone of thermal damage diminishes as the zone of vaporization increases up to 350 mJ of energy. Thereafter, both zones increase together, producing vacuoles and basophilic degeneration in the debris; 300 to 350 mJ of energy yields the best therapeutic index of efficiency and safety.

plain why the laser resurfacing is becoming the new gold standard and replacing phenol. The latter has excellent rejuvenation effect but not the accuracy.

The use of actual skin lesions allowed us to visualize Ultrapulse CO_2 laser effects that were more pronounced than seen with normal skin or an experimental animal. For example, in lasering hemangiomas it became apparent that the upper zone of the dermal capillary plexus was thrombosed. This allowed pathologic lesions to be removed without significant bleeding. The clinician can see a more accurate picture of deeper pathologic events that would often be masked by hemoglobin during excision with cold steel (Fig. 9).

The clinician can take advantage of these distal laser effects during the removal of the actinic keratosis, seborrheic keratoses, or verruca vulgaris. These lesions are removed quite efficiently after a zone of dermal-epidermal separation is produced by the cavitation effect. The pathologic lesions seem to fall off with a curettage (Fig. 10). These distal effects are also quite useful in the treatment of skin cancers. The natural cleft between basal cell cancers and normal tissue is more pronounced following laser vaporization. The superficial basal cell cancer can be shelled out without bleeding. With this clean separation between normal and pathologic tissue and with no hemoglobin blocking vision it is much easier for the clinician to see the deeper extent of the cancer (Figs. 11,12). Deep foci can be re-lasered and recuretted. This is quite similar to the approach of clinicians who use the combination of the curette and the hyphacator to produce deeper damage and shell out the resistant foci of cancer. However, the latter approach produces excessive hypopigmentation, which has not been so apparent with the laser-curette combination.

By combining these clinical-histologic corre-

lations, it is possible to come up with a new model of Ultrapulse CO_2 laser interactions in skin. This model reflects three zones: (1) the cavitation zone from the lateralization of the steam, (2) the homogenization zone reflecting the heat damage to collagen and, finally, (3) the vaporization zone. The zone of cavitation may be three diameters beyond the actual physical hit of the laser beam. The zone of homogenization may be twice the zone of physical contact. These effects extend down the dermal appendages such as the hair follicle and may result in delayed healing. It is possible to convert this data to a graph reflecting the extent of energy damage at lower millijoules being replaced by vaporization at the higher millijoules and discover that there is a best therapeutic index at approximately 350 mJ. At this setting there is the least thermal damage and yet excellent vaporization of tissue (Fig. 13).

We now advocate using the Ultrapulse CO_2 laser at 300 to 350 mJ and avoiding the 100 or 500 mJ settings unless there are specific needs for wide zones of cavitation (125 mJ) or wide zones of vaporization (500 mJ) (Fig. 14). This study on normal and pathologic tissue has enlarged our scope of understanding of Ultrapulse CO_2 laser physics. For example, direct overlap of the laser beam is not necessary and any overlapping may produce compound effects resulting in delayed wound healing.

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